Multi-Chambered Treatment Train (MCTT) For Treating Stormwater Runoff From Highly Polluted Source Areas

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ABSTRACT
A full-scaled Multi-Chambered Treatment Train (MCTT) stormwater treatment system was tested in Taiwan during the spring and summer of 2007. The MCTT was installed in a parking lot in Ping-Lin, Northern Taiwan. The site is 85% impervious and has a drainage area to the MCTT unit of 0.1 ha. The unit was designed to treat the first 10 mm of runoff from the site. A fourth chamber was added to the overall design to serve as an extra chamber for settling and convenience of sampling. A total of six storm events were sampled. Parameters analyzed included total suspended solids (SS), chemical oxygen demand (COD), ammonia-nitrogen (NH_3-N), total phosphorus (TP), lead (Pb), copper (Cu), zinc (Zn), oil/grease (O/G) and fecal coliform. Pollutant removal was calculated with both the sum of loads (SOL) and the event mean concentration (EMC) methods. Results showed the following average removal efficiencies: SS ≈ 90%; COD ≈ 45%; NH_3-N ≈ 60%; TP ≈ 50%; Pb ≈ 60%; Cu ≈ 65%; Zn ≈ 85%; fecal coliform ≈ 80%, and O/G ≈ 45%. These results are similar to those obtained for several field tests conducted in Alabama, Wisconsin and California in the US.

KEYWORDS
Field test, multi-chambered treatment train, stormwater BMP

INTRODUCTION
The multi-chamber treatment train (MCTT) consists of three treatment chambers that provide pollutant removal mechanisms including settling, dissolved air flotation, sorption, and filtration. The first chamber aerates the stormwater as it enters the treatment train and permits preliminary settling of larger diameter sediment. Stormwater is then conveyed to an inclined tray settler, where the majority of the settleable particulates are captured. Dissolved air flotation is then provided to help lift floatables and oil to the sorbent media. The last step entails passing stormwater through a sand/peat filter (FHWA, 2008). The Taiwan Environmental Protection Administration (TEPA) and National Taipei University of Technology (NTUT) began a field test on the MCTT stormwater treatment system in September 2006. The study represents a joint effort by TEPA and USEPA to demonstrate this innovative ultra-urban BMP, which was designed as an efficient, “hot-spot” runoff treatment system especially for solids, metals and toxicity (Pitt, 2002). Major tasks for the MCTT study include:

- Site selection and preparation
- MCTT design and construction
- Field monitoring and analytical work

- Analysis and synthesizing results

SITE SELECTION AND PREPARATION

An urban area in the Feitsui Reservoir watershed was chosen for the MCTT study. The reservoir is located in Northern Taiwan, about 48 km southeast of the capital city of Taipei. The watershed has an area of 303 km^2 with mostly forested land. However, there have been increasing human activities in the watershed, especially in the form of road building and tea farming. A major highway was recently completed in the watershed linking Taipei and the East Coast of Taiwan.

Feitsui Reservoir is the major source of water supply for over 4 million people in the Metropolitan Area of Taipei. Over the years the Reservoir has suffered from siltation and more recently, from eutrophication. The sources of the pollution are traced to the hundreds of tea gardens, rice fields and other agricultural areas in the watershed. Large amounts of nutrients enter the reservoir by way of stormwater runoff during storm or typhoon events. Other significant sources include runoff from towns and villages, highways, construction activities and campsites, etc.

After several reconnaissance trips by the project team, a parking lot at the Traffic Control Center of the Taiwan Highway Bureau in Ping-Lin Township was chosen as the MCTT test site. The parking lot has an area of 0.1 ha, with spaces for 45 cars and trucks. Stormwater runoff is conveyed by ditches and pipes and collected at a catch basin. The MCTT was installed downstream of the catchbasin underneath a lawn area. The outflow from the MCTT goes into a creek, which flows into a major tributary of the Feitsui Reservoir. Figure 1 below shows the location of Feitsui Reservoir and the Township of Ping-Lin.

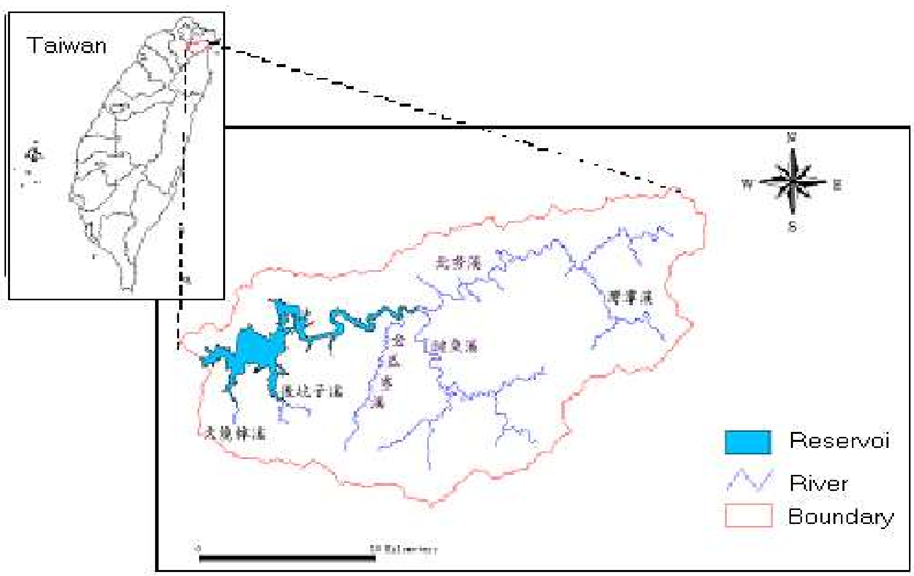

Figure 1. Location of Feitsui Reservoir and Ping-Lin Township

Figure 2 is a picture of the parking lot where the MCTT unit was installed.

Figure 2. MCTT site - Parking lot in Ping-Lin

MCTT DESIGN AND CONSTRUCTION

The MCTT unit was designed in accordance with guidelines listed in the USEPA MCTT report (USEPA, 1999) and other relevant literature (e.g., Pitt, 2002). Design details can be summarized as follows:

- The Grit Chamber or Catchbasin – The catchbasin was designed based on the estimated sediment accumulation amount as follows:
    - Annual rainfall at Ping-Lin = 4,000 mm
    - Assumed SS concentration = 100 mg/l
    - Sediment accumulation (assuming all settles for safety purposes) = 0.057 m^3/yr
    - Designed dimensions: 60 cm X 60 cm X 97.5 cm
    - Outflow pipe d = 15 cm

- Settling Chamber – The settling chamber is the most important component of the MCTT unit since it is the chamber where most of the pollutant removal takes place. The design guidelines suggest that a continuous simulation approach be used based on long-term rainfall, pollutant characteristics at the site, desired treatment volume of stormwater runoff, and targeted removal rate for designing the settling chamber. A series of design curves were obtained for many cities in the United States relating toxicant removal rates to runoff volume and hydraulic residence time. Since long-term rainfall data is not available for the Ping-Lin site, it was decided to use the design curves for Miami, Florida (Figure 3) in the US for Ping-Lin because the climate of Northern Taiwan is very similar to that of Miami. The design was based on:
    - Toxicant removal target = 55%
    - Runoff to be treated = 10 mm
    - Miami Design Curves (Figure 3)
        - Select depth = 1.5 m
        - Residence time = 24 h
        - Design flow = 10 m^3/day
    - Design chamber dimensions: 3 m X 2.2 m X 1.5 m
    - Design outflow pipe diameter determined from orifice equation
    - Include inclined plate, aerator tubes and oil sorbent mats

- Filtering Chamber design details are as follows:
  - Flow rate = 10 m^3/day, which gives a flow velocity of 1 m/day
  - Flow-through velocity selected at 2 m/day (Safety Factor = 2)
  - Design dimensions: 2.5 m X 2.2 m X 1.5m
  - Filter media: 50% sand, 50% peat, 45 cm deep, with a gravel (20-30 mm dia) underbed of 15 cm thickness. Total media depth = 60 cm.

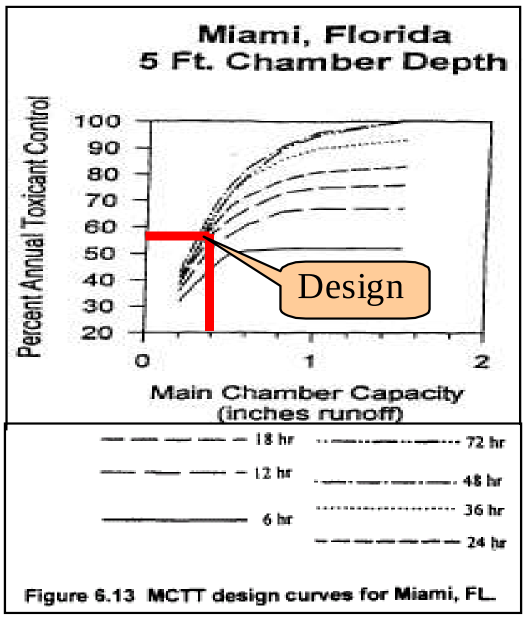

Figure 3. MCTT Design Curves for Miami, FL (USEPA, 1999)

In addition, the Research Team decided to add a fourth chamber at the outflow end, which served as a final settling chamber and especially for the convenience of taking samples. Also, pumps were used to pump water into and out of the MCTT and two flow meters were installed to measure inflow and outflow rates.

Construction of the MCTT unit began on April 12, 2007. Some delays were experienced when the construction crew encountered numerous pieces of abandoned concrete blocks during excavation, and water leakage through walls due to inadequate sealing. The problems were all resolved and the unit was completed in about a month. Figure 4 presents a schematic diagram of the MCTT system, and Figure 5 shows the completed MCTT unit at the Ping-Lin site.

MCTT MONITORING

Monitoring of the MCTT unit started in May 2007. From May through August 2007 a total of six storm events were sampled. Flow-weighted composite samples were taken at the inflow point and in the outflow sampling chamber manually and automatically, using a Sigma 900 Max automatic sampler. Water quality parameters analyzed included the following:

- Suspended solids (SS)
- Chemical oxygen demand (COD)

- Ammonia nitrogen (NH_3-N)
- Total phosphorus (TP)
- Copper (Cu)
- Lead (Pb)
- Zinc (Zn)
- Oil and grease (O/G)
- Fecal Coliform

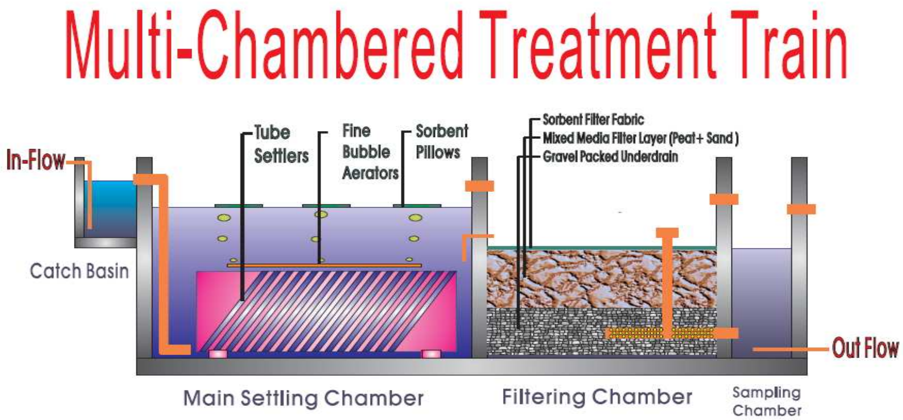

Figure 4. A schematic diagram of the MCTT unit installed at Ping-Lin.
(Note the additional fourth chamber at the end)

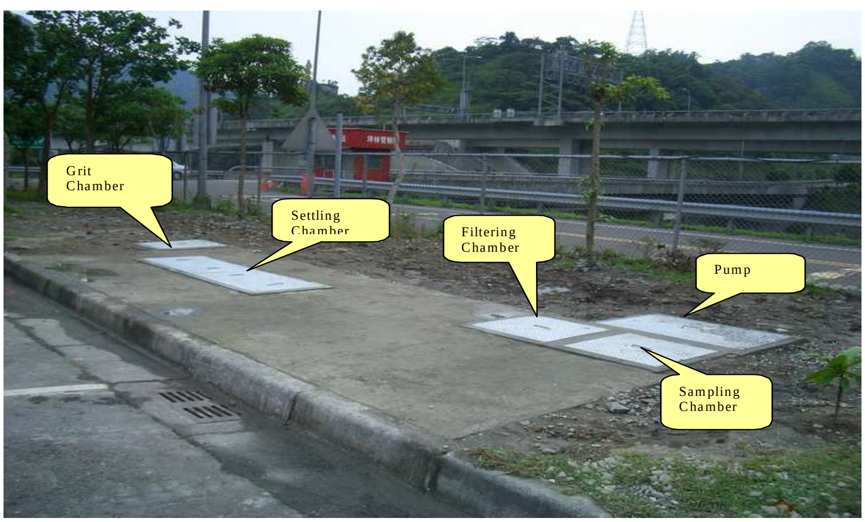

Figure 5. The Completed MCTT Unit (looking upstream)

In addition, pH, color, temperature, dissolved oxygen and rainfall amount were measured. The sampling protocol and analytical methods and procedures issued by the TEPA (TEPA, 2000) were used in the present study. These guidelines were modeled after those issued by USEPA.

Also, for SS and NH_3-N, some individual, discrete samples were taken and analyzed in order to examine the pollutant wash-off characteristic at the test site.

RESULTS AND DISCUSSION

A total of six complete storm event samples were collected. In addition, two storm events were samples prior to the MCTT installation to provide background water quality data.

Storm Events Sampled

Table 1 lists the characteristics of rainfall events sampled.

Table 1. Storm Events Sampled at the MCTT Site

Event	Date	Duration (h)	Intensity (mm/h)	Runoff Volume (m^3)
1	30/05/07	2.8	8.6	19.6
2	15/06/07	3.4	11.0	25.9
3	04/07/07	2.2	2.7	4.8
4	09/07/07	0.7	72.5	41.7
5	27/07/07	0.6	11.8	6.0
6	07/08/07	5.7	4.2	19.7

The storms ranged from short duration, high intensity to medium duration, low intensity types, with the most intense storm having a return period of about 2-3 years according to long-term rainfall statistics for the Taipei region.

Inflow Water Quantity and Quality

Inflow rates as well as quality were measured at the entry point to the first chamber of the MCTT unit. Figure 6 depicts the rainfall hyetograph and the time variation of suspended solids, which shows clearly a strong “first-flush” characteristic for the test site.

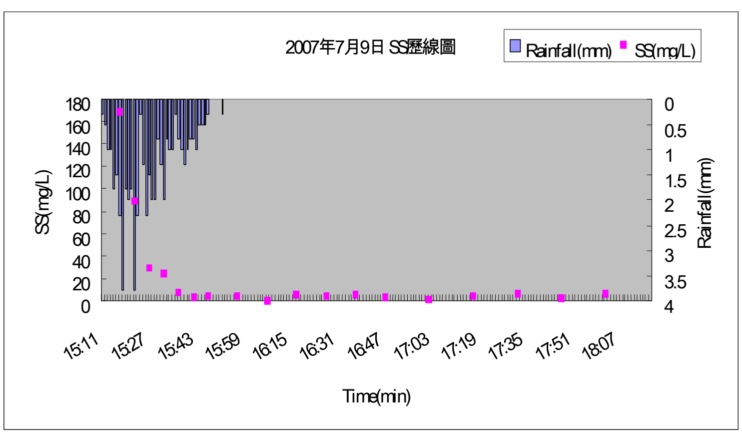

Figure 6. Rainfall and SS data collected for the 09/07/07 storm event.

The inflow event mean concentrations (EMC) for all the storm events are listed in Table 2.

Table 2. MCTT Inflow Parameter EMC Concentrations

Parameter	SS	COD	NH_3-N	TP	Cu	Pb	Zn	O/G	Color	Fecal Coliform
Date	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	(CFU/100mL)
30/05/07	58.5	110	0.39	0.068	0.020	0.030	0.210	0.90	25	8,900
15/06/07	35.5	55	0.24	0.034	0.009	0.008	0.126	0.32	25	4,675
04/07/07	6.5	35	1.63	0.060	0.014	0.007	0.152	0.88	36	11,925
09/07/07	22.5	10	0.66	0.024	0.014	0.015	0.233	0.68	25	NA
27/07/07	21.0	80	1.81	0.037	0.015	0.007	0.168	2.10	60	1,075
07/08/07	23.0	40	0.50	0.035	0.011	0.011	0.063	7.90	24	11,375
Mean	27.8	55	0.88	0.043	0.014	0.013	0.159	2.13	32	7,590

NA = Not Analyzed.

Effluent Water Quality

The effluent water samples were taken at the last chamber, or the sampling chamber. Samples were collected manually for all the storm events and flow-weighted composite samples were obtained to represent the EMCs. For the 09/07/07 storm, the rainfall intensity was very high (exceeding 70 mm/h) and the duration very short (about 40 min). There was no outflow from the MCTT unit because of excessive by-passed flow and the short storm duration. All the runoff was retained in the unit. Table 3 presents the effluent water quality data.

Table 3. MCTT Effluent Parameter EMC Concentrations

Parameter	SS	COD	NH_3-N	TP	Cu	Pb	Zn	O/G	Color	Coliform
Date	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	(CFU/100mL)
30/05/07	4	50	0.20	0.029	0.010	0.010	0.040	0.90	70	1,100
15/06/07	9	45	0.19	0.019	0.006	0.008	0.028	0.82	37	2,300
04/07/07	10.5	90	2.25	0.037	0.010	0.007	0.193	0.41	54	6,250
09/07/07	0*	0*	0*	0*	0*	0*	0*	0*	0*	0*
27/07/07	7	60	0.91	0.030	0.010	0.007	0.053	6.40	70	4,875
07/08/07	0.5	5	0.14	0.035	0.005	0.007	0.018	2.40	24	2,475
Mean	5.2	42	0.60	0.025	0.007	0.007	0.055	1.80	43	2,833

*No outflow from system.

It should be noted that the MCTT effluent water quality parameter levels were mostly low and below limits set by TEPA (TEPA, 1995). Levels of SS, COD and NH_3-N meet the TEPA Class-A water quality standards. Metal and O/G levels meet the TEPA effluent limitations.

MCTT Pollutant Reduction Efficiency

The MCTT pollutant removal efficiency was determined by both the Efficiency Ratio (ER) method, which is based on the EMC's, and the Sum-of-Loads (SOL) method, which is based on the pollutant mass fluxes flowing into and out from the MCTT system. In calculating the removal rates, the extreme values (e.g., 100% removal for the 09/07/07 storm)) were not included.

Table 4 presents the MCTT reduction efficiency calculated by the two methods. It should be noted that theoretically, the SOL method gives more accurate estimates of the removal efficiency because the method is based on a mass-balance computation and is less impacted by the inaccuracies in measuring the inflow and outflow concentrations.

Table 4. MCTT Median Pollutant Removal Efficiency by the ER and SOL Methods

Parameter	SS	COD	NH_3-N	TP	Cu	Pb	Zn	O/G
SOL (%)	89	44	61	52	65	64	85	44
ER（％）	81	24	30	42	51	50	65	14

The SOL method is considered more accurate especially if there are long-term monitoring data available. There is always the possibility that storage BMPs such as the MCTT, a detention pond, etc. will retain a certain amount of pollutants after a storm. When the next storm occurs, the residual amount might be flushed out from the BMP and therefore increase the outflow EMC and pollutant mass. In this case the ER method would be subject to a higher level of underestimation. The SOL method sums up all the inflow pollutant loads and the outflow loads and calculates the difference between the masses. If this is done over a long period of time, the SOL should provide a more accurate estimate of the true BMP reduction performance.

Table 5 provides a comparison of MCTT performance test results among studies conducted in the US and in Taiwan. It can be seen from Table 5 that the results obtained at the Ping-Lin site are similar to those obtained by the California Department of Transportation (CalTans) in Los Angeles. It should be noted that the magnitude of inflow pollutant concentrations observed at the Los Angeles site are very close to those observed at Ping-Lin.

Table 5. Comparison of MCTT Test Results in USA and Taiwan
(Average percent reduction and average effluent quality)

Parameter\ Location	**Ping-Lin (6 events)**	**Milwaukee (15 events)**	**Minocqua (7 events)**	**Birmingham (13 events)**	**Los Angeles**
SS	89 (5.2 mg/l)	98 (<5mg/l)	85 (10 mg/l)	83 (5.5 mg/l)	80
COD	44 (42 mg/l)	86 (13 mg/l)	NA	60 (17 mg/l)	NA
NH_3-N	61 (0.6 mg/l)	47 (0.06mg/l)	NA	-210 (0.31 mg/l)	NA
TP	52 (0.025 mg/l)	88 (0.02 mg/l)	80 (<0.1 mg/l)	ND	39
Cu	65 (7 ug/l)	90 (3 ug/l)	65 (15 ug/l)	15 (15 ug/l)	38
Pb	64 (7 ug/l)	96 (1.8 ug/l)	ND	93 (<2 ug/l)	50
Zn	85 (0.06mg/l)	91 (<0.02mg/l)	90 (0.015mg/l)	91 (0.018 mg/l)	85
O/G	44 (1.8 mg/l)	NA	NA	NA	41 (TPH*)
Fecal Coliform	66 (2,833 CFU/100ml)	NA	NA	NA	82

*Total Petroleum Hydrocarbon

CONCLUSIONS

- A full-scaled MCTT unit was field-tested at a parking lot site in Ping-Lin, which is a small town located in the Feitsui Reservoir watershed in Northern Taiwan. The majority of the funding was provided by the TEPA.
- The design of the Ping-Lin MCTT followed guidelines recommended in the 1999 USEPA MCTT report and other literature from the University of Alabama. An extra chamber was added at the end (outflow side) of the MCTT unit, which served as a "sampling chamber."
- The Ping-Lin parking lot has an area of 0.1 ha, with an average of 40 vehicles parked there daily. Six storm events were sampled between May and August of 2007. The median pollutant reduction rates were found to be: SS, 89%; COD, 44%; NH_3-N, 61%; TP, 52%; Cu, 65%; Pb, 64%; Zn, 85%; O?G 44%, and fecal coliform, 66%. The results are generally comparable to those obtained at test sites in the US. Some parameters, such as microtoxicity and hydrocarbons, were not measured due to equipment and resource constraints.
- Effluent water quality parameter levels were mostly low and below limits set by TEPA. Levels of SS, COD and NH_3-N meet the TEPA Class-A water quality standards. Metal and O/G levels meet the TEPA effluent limitations.
- The TEPA portion of the project was completed in September 2007. However, NTUT is maintaining the MCTT site and is continuing the monitoring work under a smaller scope, measuring only SS and nutrients. Efforts are underway to secure more funding for more extensive monitoring at the Ping-Lin site, which will include MicrotoxTM toxicity, and some hydrocarbons. Efforts are also underway to select another site for demonstration.
- Currently, most BMP designs follow the traditional "design storm" approach. In such cases the BMPs are expected to perform below expectation when storms larger than the design storm occur. On the other hand, the MCTT design is based on a continuous model simulation approach using local long-term rainfall records and on-site pollutant characteristics. It is therefore expected that the MCTT should provide removal efficiencies closer to desired efficiencies over a longer period of time.

ACKNOWLEDGEMENT
Major funding for the present study was provided by the Taiwan Environmental Protection Administration. The writers would like to thank Professor Robert Pitt of the University of Alabama at Tuscaloosa, USA for commenting on the design of the MCTT, and especially thank Dr. Elizabeth Fassman, Senior Lecturer of the University of Auckland, New Zealand, for her assistance in site selection and the implementation of sampling programs.

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